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Design, Testing, and Analysis of STATCOM and TCSC for Real-Time Simulation

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ABSTRACT

FACTS controllers are found to be effective in improving transient stability of power system. WSCC 9-bus system has been utilized as test system developed in MATLAB/Simulink software. This paper investigates the improvement of transient stability of a 3-machine 9-bus WSCC system using STATCOM and TCSC and their relative performances are studied with the help of simulation results validated with OPAL-RT real time simulator. Particular attention is paid to real-time simulation approach which provides adequate and comprehensive modeling of electric power systems (EPS) containing FACTS. Simulation results are quite encouraging and show the effectiveness of STATCOM and TCSC in improving transient stability of the test system.

Keywords**:** FACTS, FCT, Transient Stability, STATCOM, TCSC

1. INTRODUCTION

Nowadays, throughout the world the demand of the power is increasing at steep rate. Providers need to deliver higher demand of power at lower-cost with reliable operation of power system. In order to attain these, FACTS has been used for various applications such as power flow control, power quality enhancement, steady state as well as transient voltage stabilization, reactive power compensation, efficient energy ingestion, harmonic mitigation, demand control,

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power loss reduction and power factor correction [1-2]. To provide comprehensive adequate modelling and operating states of FACTS devices, the simulators should focus on the real-time solution of higher order nonlinear systems on an infinite range with higher accuracy. Furthermore, interconnection with real time simulators such as RSCAD, RTDS, OPAL-RT, ARENE URT, DigSILENT Power Factory, SCADA system.

Augmented significance of eco-friendly technologies has brought focus of the researchers toward renewable sources like wind, solar, micro-hydro, biogas and biomass so that clean, reliable, safe, efficient, and sustainable energy can be used. Power electronics device has played a key role to integrate the renewable energy sources with grid utility [3]. But the power electronics component increases harmonics distortion, which create power quality and mitigation issues for grid utilities. In the recent year, many researchers have proposed and implement various new topologies of controller such as multilevel inverter to improve the performance of FACTS device in smart grid with renewable energy system [4-5].

In this paper a state of arts of the need of advanced real time simulators along with the FACTS in enhancing stability against severe faults and irregularities with the incorporation of renewable energy sources have been discussed in Section 1. Section 2 presented an attractive literature on performance analysis of STATCOM and TCSC with various control strategies. The methodology of the proposed work has been discussed in Section 3. Simulation modelling of STATCOM and TCSC has been implemented in Section 4 and Section 5 respectively. Simulation results for different fault locations and Fault Clearing Time (FCT) have been discussed in Section 6. Finally, conclusions are included in Sec. 8.

2. VARIOUS CONTROL STRATEGIES OF FACTS

FACTS controllers provide voltage support with shunt controllers at critical buses and normalize power flow using series controllers in critical lines in the power system [6].

2. 1. Static Synchronous Compensator (STATCOM)

STATCOM has a voltage source converter and a dc capacitor coupled to the transmission line with potential transformer. The general configuration of the STATCOM and its characteristics as shown in Figure 1.

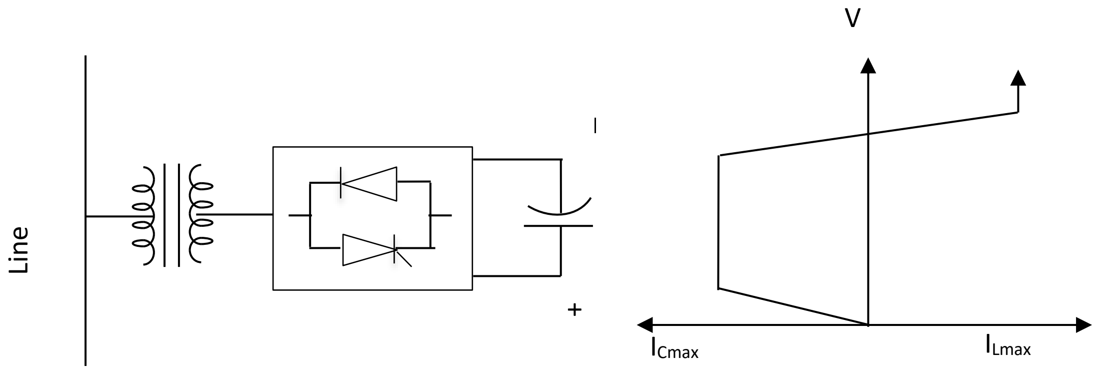

Figure 1. General configuration & V-I characteristics of STATCOM.

STATCOM controls the line voltage with the help of ac voltage controller by managing the reactive power flow between power system and STATCOM. The dc controller directs dc voltage over the dc capacitor. PI (proportional integral) cascaded controller is used for both regulators in conventional control schemes [7-8].

To beat the constraints in the linear PI-controller, many of the researches have suggested nonlinear control schemes for the STATCOM. A novel pole-shifting controller for current source converter based STATCOM is proposed to increase the reliability and stability of power system and also effectiveness in damping oscillations [9] over VSC-STATCOM and SVC. The feedback linearization approach has been used in view of dropping the system nonlinearities hence forcing a coveted linear dynamics to control system [10-13]. Dissipativity-based control for VSI-STATCOM deals with regulation of unbalanced supply voltages and currents [14]. In wind generation system, a Doubly Fed Induction Generator (DFIG) is a better alternative to deal with the increased power demand. Synchronisation with the grid is an important factor for DFIG on occurrence of severe faults. Authors have shown the capability of the Enhanced Field Oriented Control (EFOC) technique using MATLAB/Simulink [15].

A STATCOM controller named as Interconnection Damping Assignment (IDA) based Passivity Control (PBC) has been proposed to overcome the limitation of a feedback linearizing controller and conventional power system stabilizer [16]. Several researchers have used artificial intelligence in making more effective controller to improve the stability of utility. A neuro-fuzzy PI controller for Battery Energy Storage (BES) system based VSI-STATCOM implemented in MATLAB/Simulink. Modified Particle Swarm Optimization (MPSO) is effectively used to optimize the controller parameters. It is observed that, with assimilation of a fuel cell, the real power compensation ability and the transient stability is improved [17]. An adaptive Power Oscillation Damping (POD) controller has given better performance over conventionally used controller.

Modified Recursive Least Square (RLS) algorithm is applied to estimate the controller parameters using PSCAD/EMTDC [18]. A centralized control scheme of using a Small Dynamic Braking Resistor (SDBR) in series with a STATCOM has been proposed in enhancing the grid-connected wind farm stability modelled in PSCAD/EMTDC simulation tool by minimizing the blade–shaft torsional oscillation [19].

2. 2. Thyristor Controlled Series Capacitor (TCSC)

TCSC, an imperative FACTS device has numerous tasks in the operation and controlling of power system such as to provide voltage support, schedule power flow, damp out power oscillations in turn establishing transient stability. The schematic diagram of TCSC and its operating characteristics is revealed in Figure 2.

Reactive impedance (X_{TCSC}) can be tuned by firing angle α given by Eq. (1) and Eq. (2)

$$X_{TCSC} = \frac{X_C X_L(\propto)}{X_L(\propto) - X_C} \tag{1}$$

where,

$$X_L(\propto) = X_L \frac{\pi}{\pi - 2\propto - \sin\propto} \tag{2}$$

To enhance transient stability, an Improved Particle Swarm Optimization (IPSO) has been utilized to outline the Automatic Generation Control (AGC) for TCSC. MATLAB/Simulink environment has been used to show the superior operation of TCSC over TCPS and SSSC coordinated with AGC to damp out tie-line oscillations/area frequencies [20]. A PID controller based TCSC has been used to analyse the effect of fixed and variable series compensation on Single Machine Infinite Bus (SMIB) system for different fault clearing time using MATLAB / Simulink. The simulation results show that with the increase in compensation first swing of the machine is reduced while critical clearing angle is increased [21].

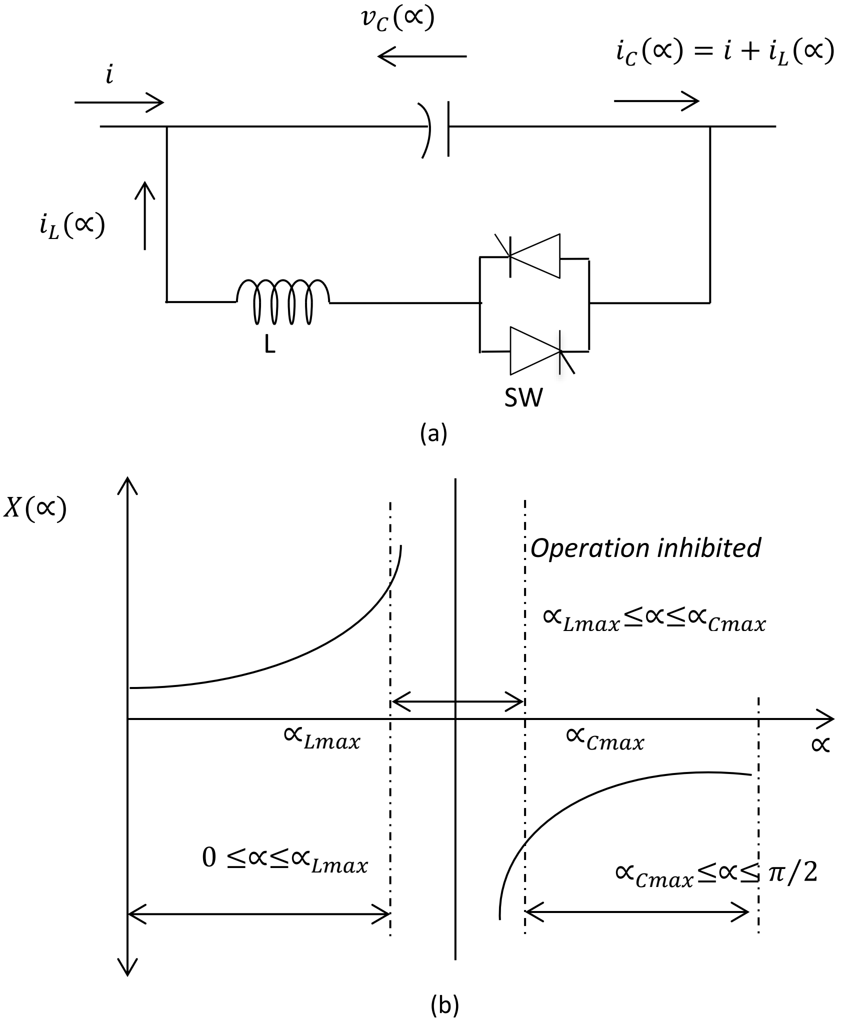

Figure 2. (a) Schematic diagram (b) V-I characteristics of TCSC.

It is observed that, multi-machine 9-bus system has a negligible steady state error. A non-linear zero dynamic design [22] control scheme for TCSC enhances the effectiveness, reduce complexity and perform satisfactory operation. According to the first benchmark model of IEEE, Sub-Synchronous Resonance Damping Controller (SSRDC) for the Gate-Controlled Series Capacitor (GCSC) is applied for effectively damping the sub-synchronous resonance in

Wind Turbine Generator System (WTGS). The performance of GCSC and TCSC in damping SSR is analysed by monitoring the wind generator electric torque, results reveals that GCSC takes 0.2 s less than TCSC which takes 0.4 s to damp SSR oscillations [23].

Furthermore, ectropy based FACTS controllers have been used extensively to preserve synchronism between generators. Simulation results have shown the potential of the proposed controller which effectively increase critical clearing time of the system by more than 30% as compared to uncompensated system [24].

3. METHODOLOGY

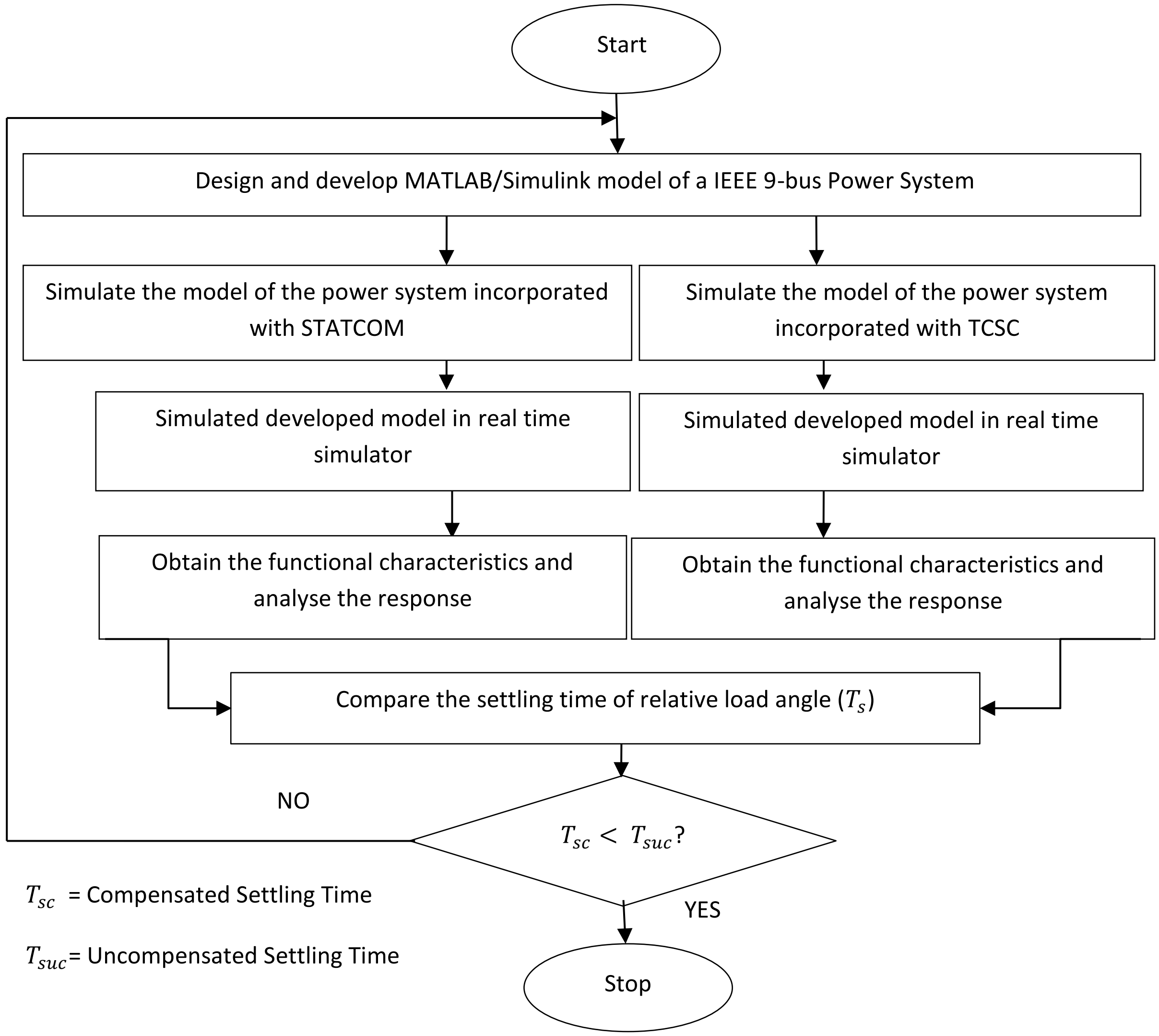

Figure 3. Flowchart of the proposed work.

The proposed work is divided into four steps as discussed in flowchart of the methodology in Figure 3; in the initial state a MATLAB/Simulink model of WSCC 3- Machine 9-bus test system has been developed. After that the test system implemented with STATCOM [25] or TCSC has been simulated and transient stability has been analyzed for three phase fault in the MATLAB/Simulink. The same process is validated in the real time environment using OPAL-RT. FACTS device has been suggested accordingly by comparing damping characteristics.

4. REAL TIME SIMULATION OF STATCOM USING OPAL-RT

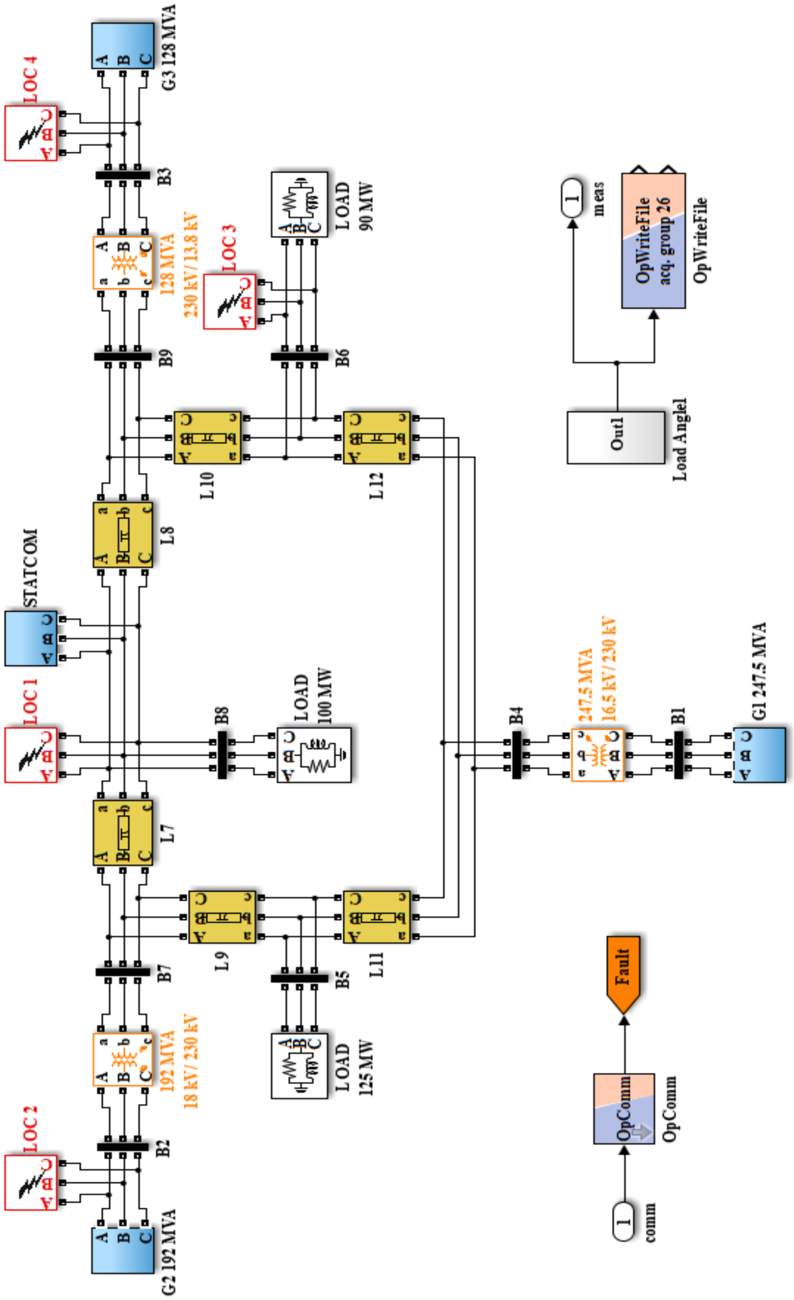

Figure 4. OPAL-RT **based** model of WSCC 3-machines 9-bus system implemented with STATCOM.

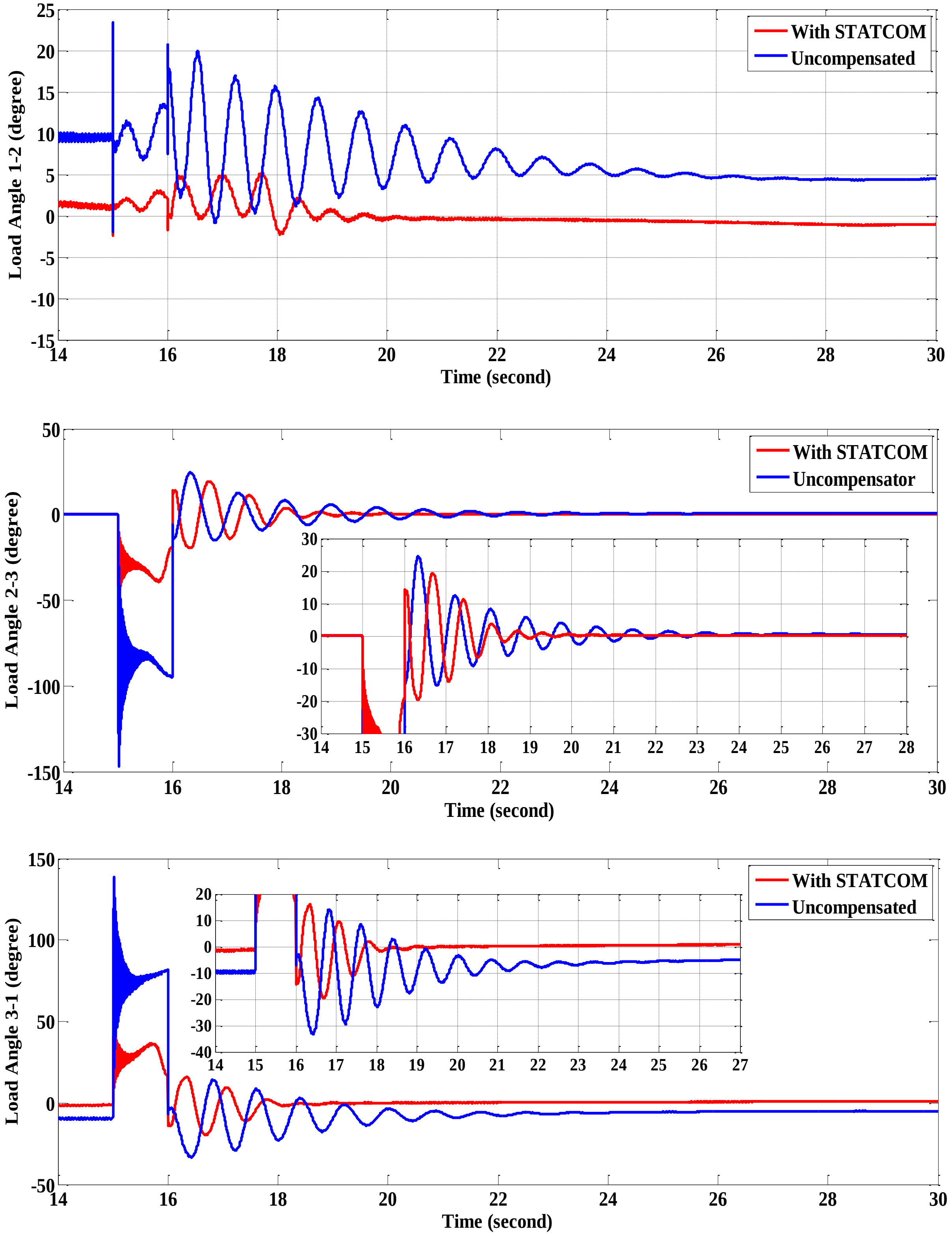

Figure 5. Variation of relative load angular position with time with fault at location LOC2 for FCT = 1 Second.

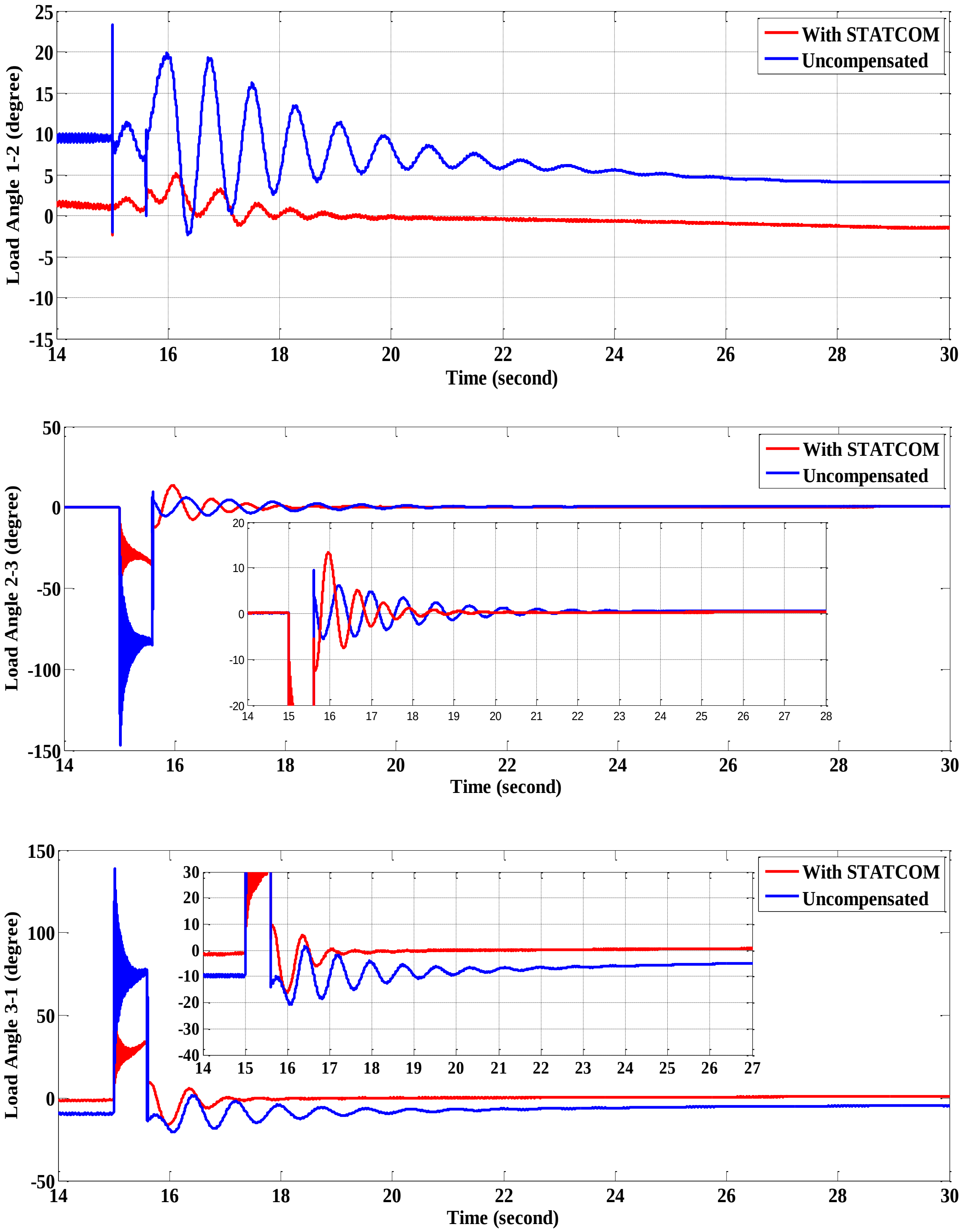

Figure 6. Variation of relative load angular position with time with fault at location LOC2 for FCT = 0.6 Second.

The modelling and simulation of 3-Machine, 9-Bus WSCC system with STATCOM has been carried out in the real-time environment using MATLAB and OPAL-RT simulator. Whole system is introduced with fault at different locations occurring one at a time as illustrated by master block of the OPAL-RT based model in Figure 4.

Figure 5 represents variations of relative load angular positions for delt1_2, delt2_3 and delt3_1 with time for MM system implemented with and without STATCOM and fault occurring in it at the instant of 15 seconds. It has been analyzed for three phase fault at four different locations for a Fault Clearing Time (FCT) of one second.

As the fault takes place in the system, the system with STATCOM shows a much faster operation in damping post fault oscillations rather than in the system without controller. In case of fault at location 2, system with STATCOM attains stability 6.7, 6.3 and 6.0 seconds earlier than the uncompensated system for relative load angles 1-2, 2-3 and 3-1 respectively.

Figure 6 represents variations of relative load angles 1-2, 2-3 and 3-1 with time for MM system implemented with and without STATCOM and fault occurring in it at the instant of 15 seconds at generator 2 terminals for the fault clearing time (FCT) of 0.6 second.

5. REAL TIME SIMULATION OF TCSC USING OPAL-RT

The modelling and simulation of 3-Machine, 9-Bus WSCC system with TCSC has been carried out in the real-time environment using MATLAB and OPAL-RT simulator.

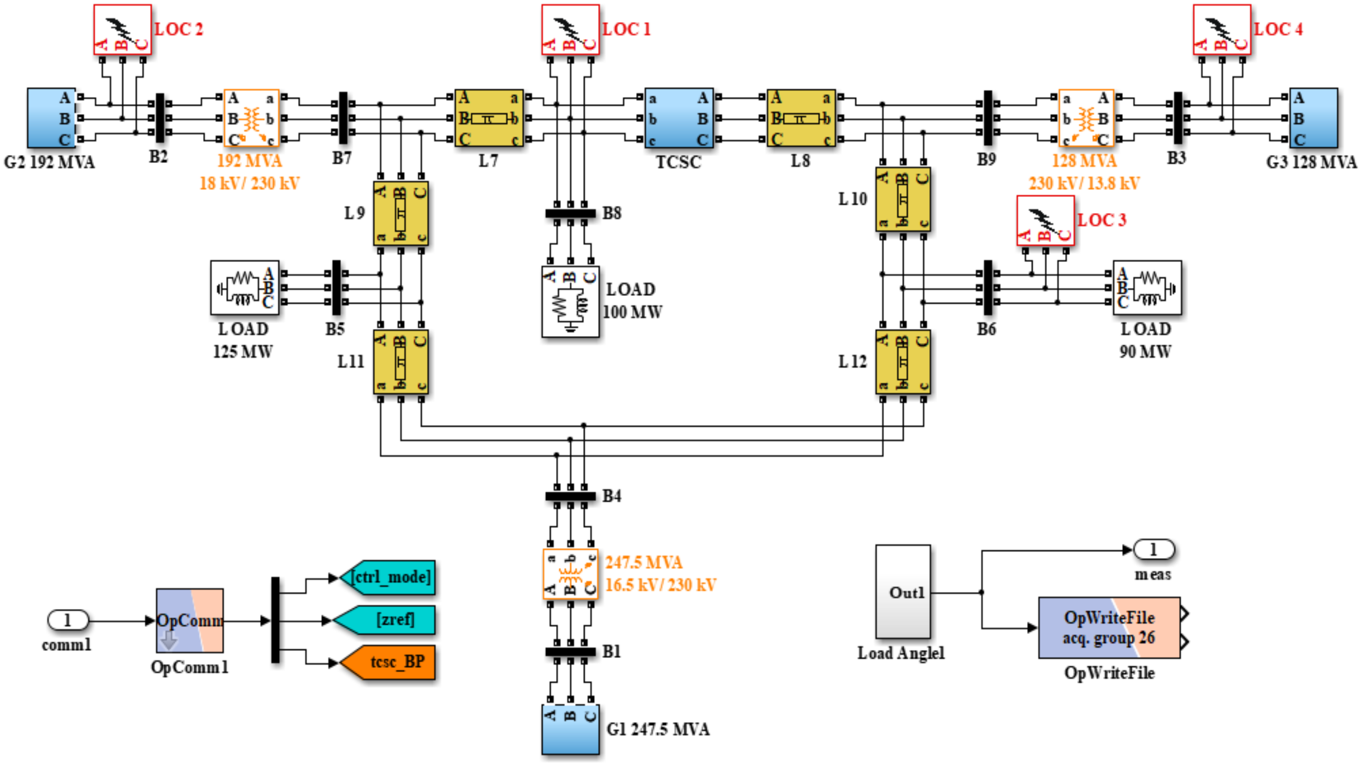

Figure 7. OPAL-RT based model of WSCC 3-machines 9-bus system implemented with TCSC.

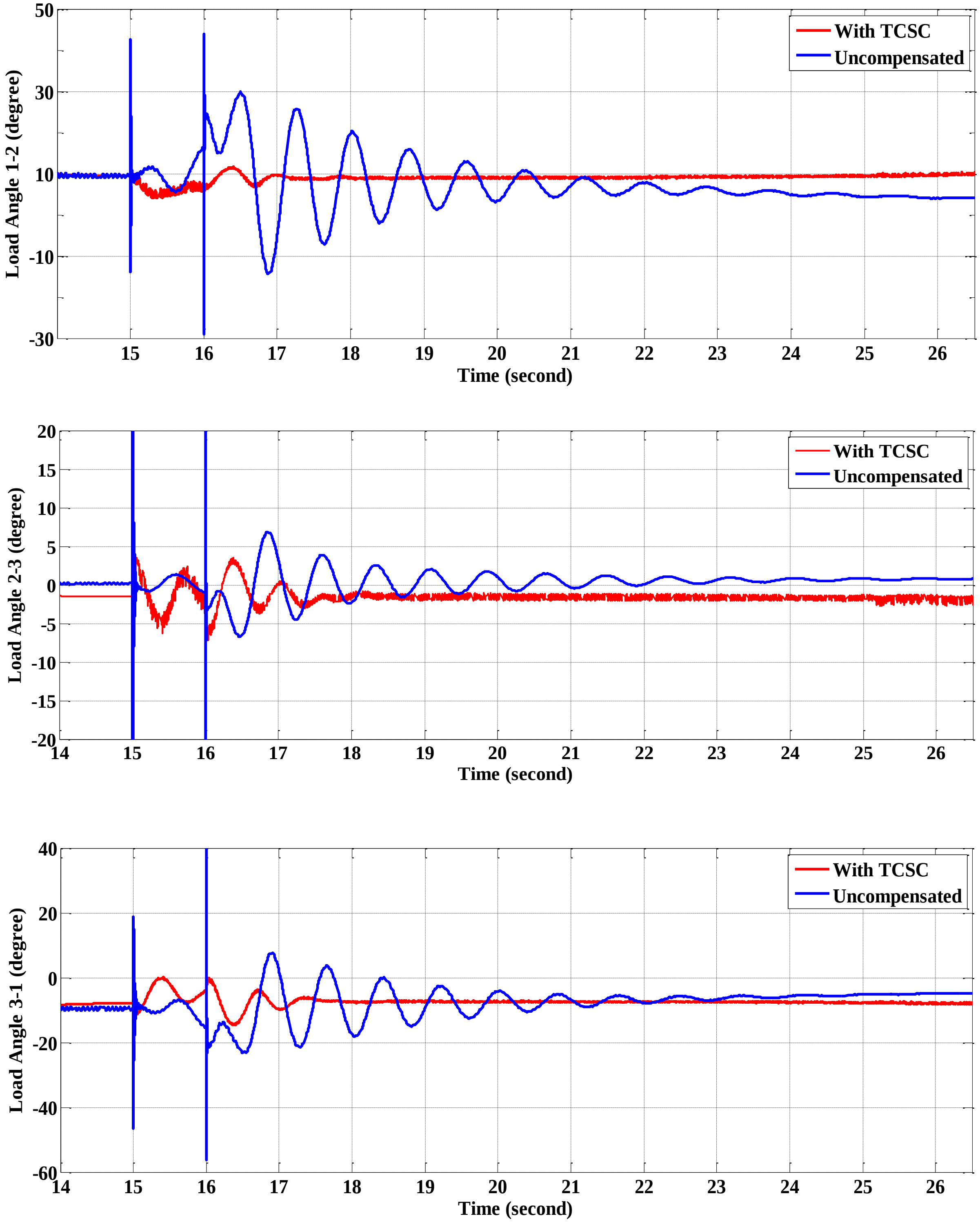

Figure 8. Variation of relative load angular position with time with fault at location LOC1 for FCT = 1 Second

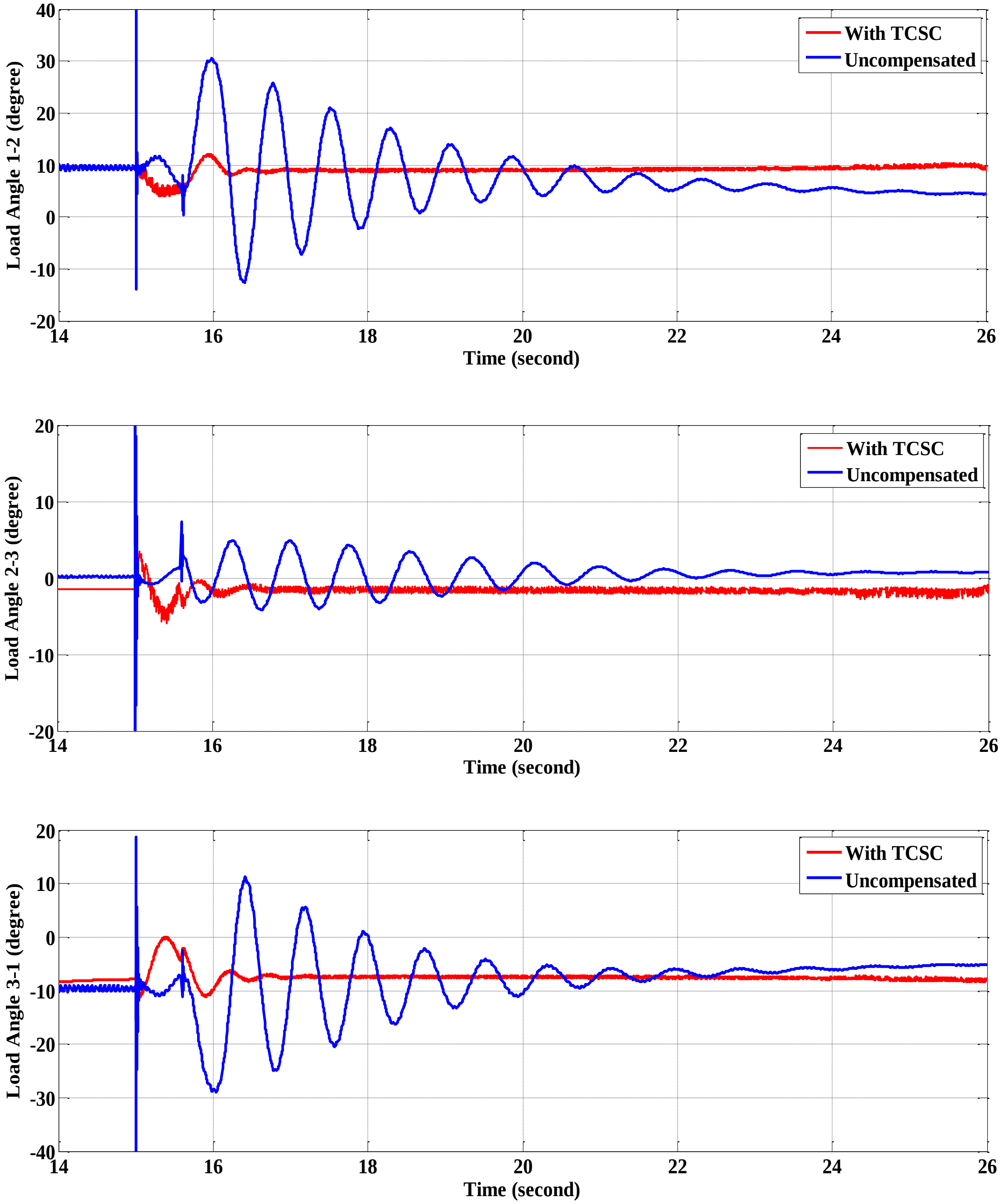

Figure 9. Variation of relative load angular position with time with fault at location LOC1 for FCT = 0.6 Second.

Whole system is introduced with fault at different locations as illustrated by master block of the OPAL-RT based model in Figure 7. Figure 8 represents variations of relative angular positions for delt1_2, delt2_3 and delt3_1 with time for MM system implemented with TCSC and fault occurring in it at the instant of 15 seconds. It has been analyzed for three phase fault at four different locations for a fault clearing time (FCT) of one second.

Figure 9 represents variations of relative load angles 1-2, 2-3 and 3-1 with time for MM system implemented with and without TCSC and fault occurring in it at the instant of 15 seconds at middle of the transmission line for the fault clearing time (FCT) of 0.6 second.

6. SIMULATION RESULTS

6. 1. STATCOM

The time taken to attain stability, steady state stable value and maximum overshoot of relative load angular positions (delt1_2, delt2_3 and delt3_1) with time for different fault locations are given in Table 1, Table 2 and Table 3 respectively. It can be observed from Table 1 that the three phase short circuit fault at generator end (LOC2 and LOC4) is most severe while fault at the middle of the transmission line (LOC1) is more severe than the same fault occurring at load side (LOC3) as illustrated by the values of time taken to attain stability of relative load angles 1-2, 2-3 and 3-1.

Table 1. Time taken to attain stability (second)

Location	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
LOC 1	9.8	3.8	10.0	5.1	9.5	4.0
LOC 2	11.2	4.5	10.2	3.9	9.7	3.7
LOC 3	8.0	3.5	6.0	3.5	9.2	3.9
LOC 4	10.4	4.0	11.2	4.5	12.2	4.8

Table 2. Steady state stable value (degree).

Location	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
LOC 1	4.0	-0.3	0.7	0.7	-5.2	-0.1
LOC 2	4.6	-0.3	0.6	0.3	-5.2	0.2
LOC 3	5.1	0.0	0.4	0.1	-5.1	-0.1
LOC 4	4.2	-0.8	1.1	0.7	-5.2	0.2

Table 3. Maximum overshoot (degree).

Location	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
LOC 1	25.4	5.4	6.2	2.4	12.8	6.0
LOC 2	15.4	5.1	23.9	19.1	19.4	15.5
LOC 3	19.6	5.5	12.1	3.7	13.8	9.0
LOC 4	50.6	60.2	47.0	55.1	3.5	3.1

Table 4. Time taken to attain stability (second).

Fault Clearing Time	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
0.2	9.9	2.4	8.9	3.2	8.8	1.4
0.4	10.1	3.4	9.2	3.7	8.9	2.5
0.6	10.4	3.8	9.3	3.8	9.3	3.2
0.8	10.8	4.2	9.7	3.9	9.7	3.5
1.0	11.2	4.5	10.0	3.9	10.0	3.7

Table 5. Steady state stable value (degree).

Fault Clearing Time	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
0.2	4.7	0.3	0.7	0.2	-5.9	-0.5
0.4	4.4	0.0	0.6	0.3	-5.7	-0.3
0.6	4.6	0.0	0.6	0.0	-5.6	-0.1
0.8	4.4	-0.2	0.6	0.6	-5.3	-0.1
1.0	4.6	-0.3	0.6	0.3	-5.2	0.2

Table 6. Maximum overshoot (degree).

Fault Clearing Time	1-2		2-3		3-1	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
0.2	11.1	2.2	2.0	0.7	5.0	1.2
0.4	15.5	3.8	7.7	2.7	3.6	3.2
0.6	15.3	5.2	5.6	13.4	7.3	5.9
0.8	13.3	11.8	14.0	19.0	11.8	16.8
1.0	15.4	5.1	23.9	19.1	19.4	15.5

The steady state error in the stable value is nearer to zero when implemented with STATCOM rather than the uncompensated system in which the error is of 5 degrees. For LOC 2 (fault at Generator 2), with the incorporation of STATCOM, maximum overshoot is reduced to 1/3rd, 4/5th and 4/5th of the value of uncompensated load angle 1-2, 2-3 and 3-1 respectively.

The time taken to attain stability better known as settling time, steady state stable value and maximum overshoot of relative load angles (1_2, 2_3 and 3_1) with time for different fault clearing time are tabulated in Table 4, Table 5 and Table 6 respectively. Fault clearing time is varied in the steps of 0.2 seconds and its effect is observed.

- The increase in the value of settling time from 9.9 seconds to 11.2 seconds in case of uncompensated and 2.4 seconds to 4.5 seconds in case with STATCOM considering load angle 1-2 clearly shows that the time taken to attain stability also increases with the increase in fault clearing time in both the cases.
- As the fault clearing time increases from 0.2 second to 1 second, steady state stable values of relative load angles1-2, 2-3 and 3-1 of system with and without STATCOM remains almost constant.
- A drastic change in the value for relative load angle 2-3 from 2.0 degrees to 23.9 in case of uncompensated system and a hike from 0.7 to 19.1 degrees clarifies that maximum overshoot value of uncompensated as well as compensated relative load angle 1-2, 2-3 and 3-1 increases with the increase in the fault clearing time.

6. 2. TCSC

The time taken to attain stability, steady state stable value and maximum overshoot of relative load angles (1_2, 2_3 and 3_1) with time for different fault locations are given in Table 7, Table 8 and Table 9 respectively.

It can be observed from Table 7 that the three phase short circuit fault at generator end (LOC2 and LOC4) is most severe while fault at the middle of the transmission line (LOC1) is more severe than the same fault occurring at load side (LOC3) as illustrated by the values of time taken to attain stability of relative load angles 1-2, 2-3 and 3-1. The steady state error in the stable value is nearer to zero when implemented in the uncompensated system rather than with TCSC in which the error is much larger as observed from Table 8. Table 9 shows the effect of TCSC in reducing maximum peak overshoot value.

Table 7. Time taken to attain stability (second).

Location	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
LOC 1	9.8	1.1	10.0	2.1	9.5	1.7
LOC 2	11.2	2.0	10.2	2.5	9.7	2.5
LOC 3	8.0	1.1	6.0	1.9	9.2	1.7
LOC 4	10.4	2.1	11.2	2.6	12.2	3.1

Table 8. Steady state stable value (degree).

Location	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
LOC 1	4.0	9.3	0.7	-1.7	-5.2	-7.2
LOC 2	4.6	7.2	0.6	-0.7	-5.2	-6.5
LOC 3	5.1	-17.9	0.4	5.0	-5.1	13.7
LOC 4	4.2	-10.9	1.1	3.9	-5.2	6.9

Table 9. Maximum overshoot (degree).

Location	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
LOC 1	25.4	2.3	6.2	4.9	12.8	11.1
LOC 2	15.4	2.9	23.9	10.7	19.4	15.0
LOC 3	19.7	34.4	12.1	6.0	13.8	15.4
LOC 4	50.6	57.7	47.0	57.2	3.5	3.6

For fault at Generator 2, with the incorporation of TCSC, maximum overshoot is reduced to approximately 1/5th, 2/5th and 4/5th of the value of uncompensated load angle 1-2, 2-3 and 3-1 respectively.

As the fault takes place in the system, the system with TCSC shows a much faster operation in damping post fault oscillations rather than in the system without controller. In case of fault at location 2, system with TCSC attains stability 9.2, 7.5 and 7.5 seconds earlier than the uncompensated system for relative load angles 1-2, 2-3 and 3-1 respectively.

The time taken to attain stability, steady state stable value and maximum overshoot of relative load angles (1_2, 2_3 and 3_1) with time when a three phase fault occurs at middle of the transmission line for different fault clearing time are given in Table 10, Table 11 and Table 12 respectively.

Table 10. Time taken to attain stability (second).

Fault Clearing Time (sec)	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
0.2	6.8	1.1	6.1	1.7	5.6	1.5
0.4	8.7	1.1	6.6	1.7	5.8	1.5
0.6	9.0	1.3	9.6	1.9	8.4	1.4
0.8	9.3	1.2	9.7	1.9	8.9	1.4
1.0	9.8	1.1	10.0	2.1	9.5	1.7

Table 11. Steady state stable value (degree).

Fault Clearing Time (sec)	**1-2**		**2-3**		**3-1**	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
0.2	6.6	9.2	0.4	-1.2	-7.2	-7.8
0.4	5.1	9.4	0.4	-1.3	-7.6	-5.2
0.6	4.7	9.3	0.8	-1.5	-6.1	-7.5
0.8	4.9	8.8	0.8	-1.4	-5.3	-7.3
1.0	4.0	9.3	0.7	-1.7	-5.2	-7.2

Table 12. Maximum overshoot (degree)

Fault Clearing Time (sec)	1-2		2-3		3-1	
	Uncomp	**Comp**	**Uncomp**	**Comp**	**Uncomp**	**Comp**
0.2	9.2	2.4	1.3	3.5	5.6	9
0.4	15.8	3.1	3.3	5.0	7.8	1.1
0.6	25.9	2.8	4.1	1.2	17.3	5.1
0.8	23.8	2.5	1.8	3.5	14.2	3.9
1.0	25.4	2.3	6.2	4.9	12.8	11.1

- Time taken to attain stability increases with the increase in fault clearing time in case of uncompensated system while the same in system with TCSC remains almost constant.
- As the fault clearing time increases from 0.2 second to 1 second, error in the steady state stable values of relative load angles 1-2and 3-1 of uncompensated system gradually decreases while for 2-3 there is a small increase in the steady state value. System with TCSC shows a nearly constant behaviour irrespective of FCT but with larger value of steady state error.
- Maximum overshoot value of uncompensated relative load angles 1-2, 2-3 and 3-1 increases, on the other hand with TCSC relative load angles 1-2, 2-3 and 3-1 mostly remains constant to a much smaller values.

7. CONCLUSIONS

Performance evaluation in terms of transient stability improvement has been studied and the load angle variations with time have been plotted in both the cases by varying the location of fault as well as fault clearing time (FCT). Simulation results are quite encouraging and show the effectiveness of STATCOM and TCSC. By comparing the results, it has observed that the settling time of relative load angles decreases in a much greater proportion while implementing TCSC as compared to STATCOM.

Considering steady state error, STATCOM shows much better results than TCSC. TCSC left STATCOM much behind in suppressing maximum peak overshoot after the occurrence of three phase fault in MM system. Investigation also reveals that irrespective of fault clearing time (FCT), both STATCOM and TCSC improves the transient response of system while in case of uncompensated system, steady state stable value, time taken to attain stability and maximum value of overshoot increases with increase in FCT. Real time simulation with OPAL-RT OP4510 of MATLAB/Simulink model of STATCOM and TCSC serves the purpose of physical validation.

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